A SYSTEM FOR THE CONTINUOUS MEASUREMENT OF OXYGEN CONSUMPTION, DETERMINATION OF CARBON DIOXIDE PRODUCTION AND RESPIRATORY EXCHANGE RATIO

GEORGE LISTER, Jr.

1973

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A SYSTEM FOR THE CONTINUOUS MEASUREMENT OF OXYGEN CONSUMPTION, DETERMINATION OF CARBON DIOXIDE PRODUCTION AND RESPIRATORY EXCHANGE RATIO

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Lastly, I would like to thank my family who has provided for me an atmosphere of understanding and support in which to pursue my education.

TABLE OF CONTENTS

Having breathed an atmosphere filled with the products of his own spiritual combustion, he remembers reading somewhere that, in the neighborhood of a sulphur works, even a sparse vegetation can only survive if it is sheltered from the wind.

-- Dag Hammarskjold

INTRODUCTION

Measurement of oxygen consumption ($\dot{V}_{O_2}$) serves two primary functions in clinical medicine. As a form of indirect calorimetry, $\dot{V}_{O_2}$ can be used to assess the energy metabolism of individuals. The metabolic rate is calculated from the known heats of oxidation of protein, fat, and carbohydrate and the relative amounts metabolized of each of these foodstuffs.[1,2] Secondly, the rate of oxygen consumption is necessary for the calculation of blood flow by the Fick method:

Blood Flow = Oxygen Consumption / (Arterial Oxygen Content - Venous Oxygen Content).[3]

At present this is the method most frequently utilized for determining pulmonary and systemic blood flow at the time of cardiac catheterization.

Because of the difficulty of measuring $\dot{V}_{O_2}$ in children, especially infants, values are commonly estimated from tables or regression equations relating surface area, height, weight, age or heart rate to oxygen consumption.[4-7] These estimates, however, have considerable variability and are clearly of no use in metabolic studies. Furthermore, predicted $\dot{V}_{O_2}$ may be most erroneous in the sick[3,8,9] or the sedated child;[10] the cardiac output thus obtained would be misleading.

There is, therefore, a need for a means of measuring $\dot{V}_{O_2}$ which is simple, applicable to children of all ages, and useful during cardiac catheterization. This thesis describes in detail a new system for deter-

mining oxygen consumption and carbon dioxide production ($\dot{V}_{CO_2}$) which is inexpensive and portable and was developed to satisfy these criteria.

As previous reports of measurements of $\dot{V}_{O_2}$ have ignored the errors due to changes in respiratory exchange ratio (R),[6, 11-13] derivations of $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ are included as well as a method for correcting determined $\dot{V}_{O_2}$ for variations in R. The results of $\dot{V}_{O_2}$, $\dot{V}_{CO_2}$, and R, determined in a series of 15 infants studied during cardiac catheterization using this method, are reported.

METHOD

The method for measurement of oxygen consumption is based on the flow through technique.[14] The subject is placed in a chamber through which flows a stream of room air. This allows continuous entry into the system of fresh air while expired gas is removed and collected. The room air is thereby diluted with expired gas; the mixture is sampled and oxygen concentration measured. The oxygen consumption is calculated by multiplying the flow rate of air through the system by the difference in oxygen concentrations of the room air flowing in and the mixed expired gas. Similarly, this mixed expired gas may be sampled for carbon dioxide concentration; flow rate multiplied by the difference in carbon dioxide concentrations between mixed expired gas and room air yields carbon dioxide production. The equations for calculating $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$, as derived in the appendix, are:

$$\dot{V}_{O_2}\ \text{(STPD)} = \dot{V}_S(F_{I_{O_2}} - F_{S_{O_2}})\ \text{(STPD) and}$$

$$\dot{V}_{CO_2}\ \text{(STPD)} = \dot{V}_S(F_{S_{CO_2}} - F_{I_{CO_2}})\ \text{(STPD),}$$

where $\dot{V}_S$ is the flow rate through the system, and F_I and F_S are the gas concentrations of inspired room air and the sampled mixed expired gas respectively. These values must be further corrected for variations in the respiratory exchange ratio ($\dot{V}_{CO_2}/\dot{V}_{O_2}$).

<u>The System</u>

Referring to figures 1 and 2, room air is drawn around the sides of a loosely fitting lucite hood and into the system at a rate $\dot{V}_L$ by means of

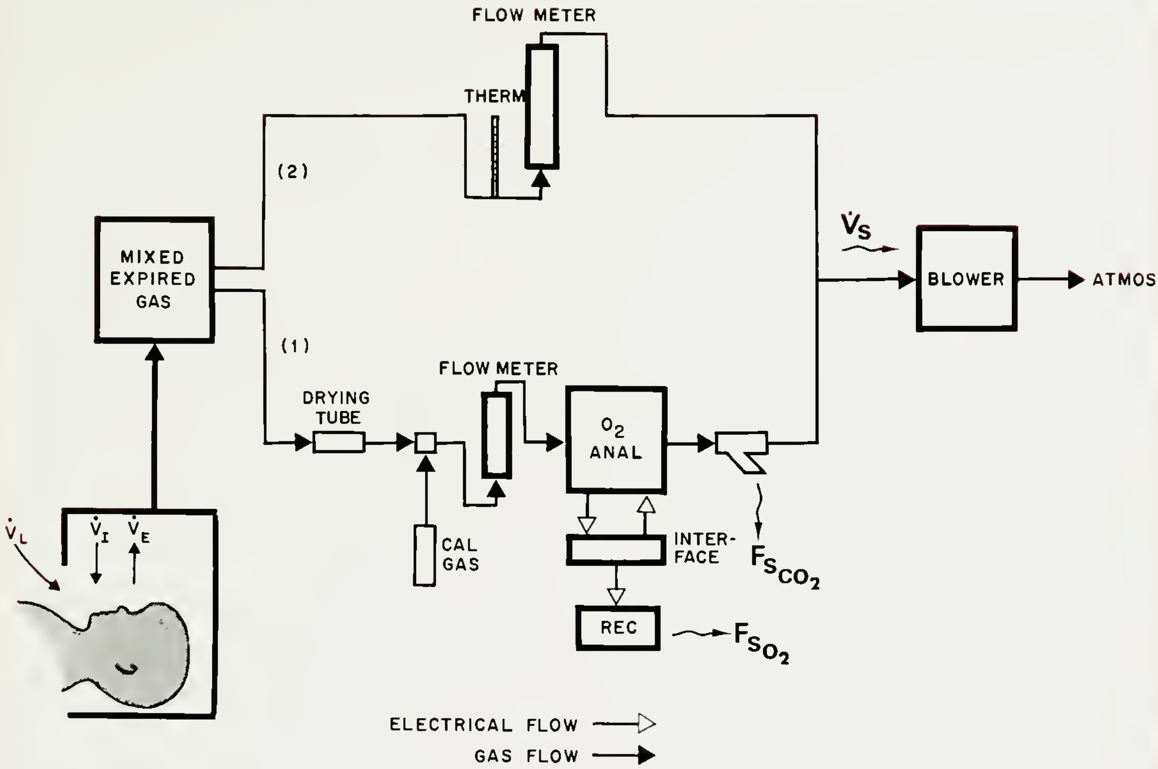

Figure 1. Block diagram of flow through system.

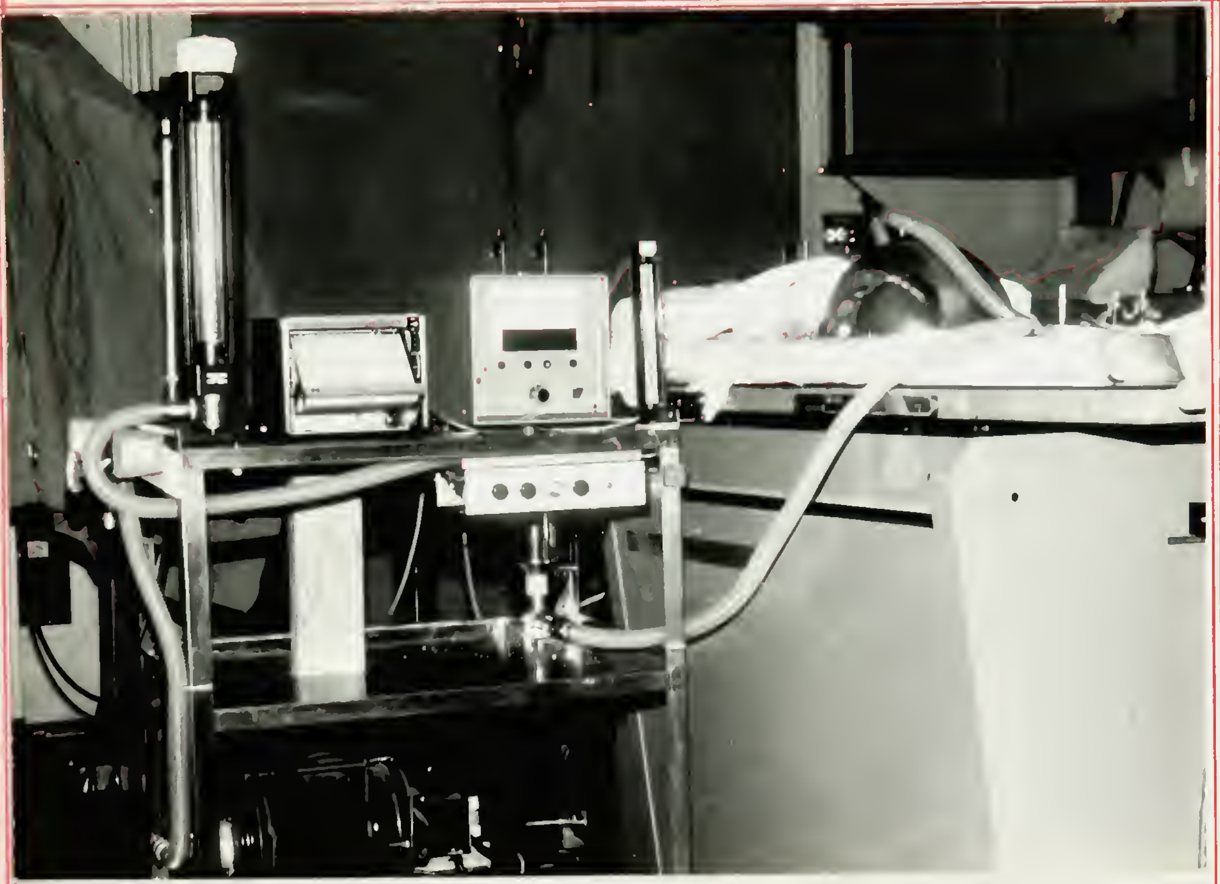

Figure 2. Flow through system in operation.

a blower.* As the subject breathes ($\dot{V}_I$, $\dot{V}_E$), the room air-expired gas mixture flows+ into a chamber filled with glass balls to insure adequate mixing. From here there are two parallel circuits:

1. A small proportion (150 ml/min) of the mixed expired gas is directed through the oxygen analyzer** for continuous sampling and recording of oxygen concentration ($F_{S_{O_2}}$). Distal to the analyzer is an outlet for sampling gas for carbon dioxide concentration ($F_{S_{CO_2}}$).
2. The remainder of the gas passes through a flow meter≠ for measurement of flow rate.

As the system is designed, the total flow of gas through the system ($\dot{V}_S$), i.e., that amount passing through the blower, is the sum of the flow meter recording and the flow through the oxygen analyzer.

<u>Procedure</u>

The system was allowed to warm up for one hour prior to use to achieve stability. The oxygen analyzer control was set on 25% range, room air was drawn through the system, and the recorder baseline was set on 20.93% oxygen. Then, in order that full scale deflection of the

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*Series 329 AS, Rotron Manufacturing Co. Woodstock, New York.

+Gas flow carried by U-mid/60 breathing hose 3/4", Bard-Parker.

**Servomex Type OA 150. Crowborough, Sussex, England. (See figures 3 and 4 for circuit diagram of power supply and electrical interface.)

≠Fisher and Porter Model 10A 3565A.

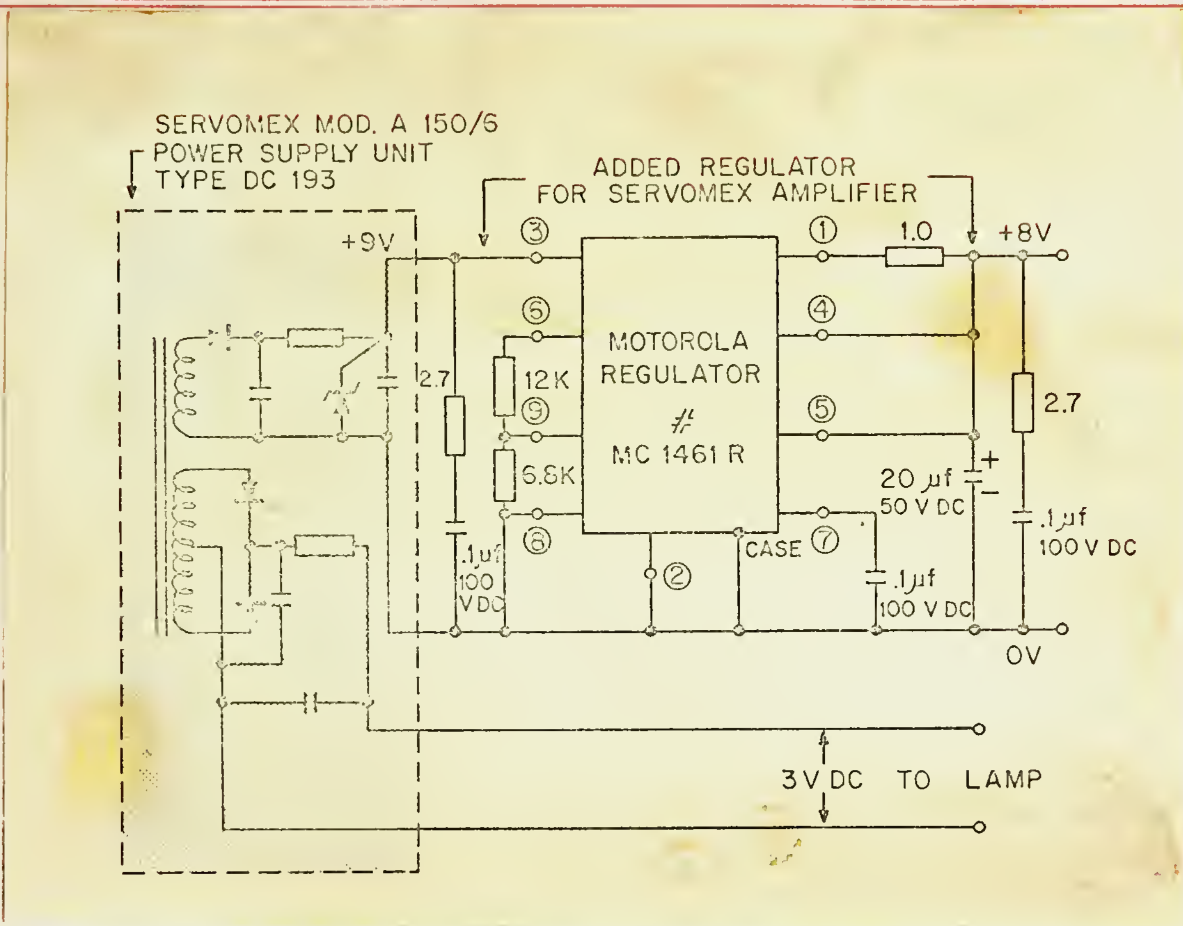

Figure 3. Power supply for oxygen analyzer.

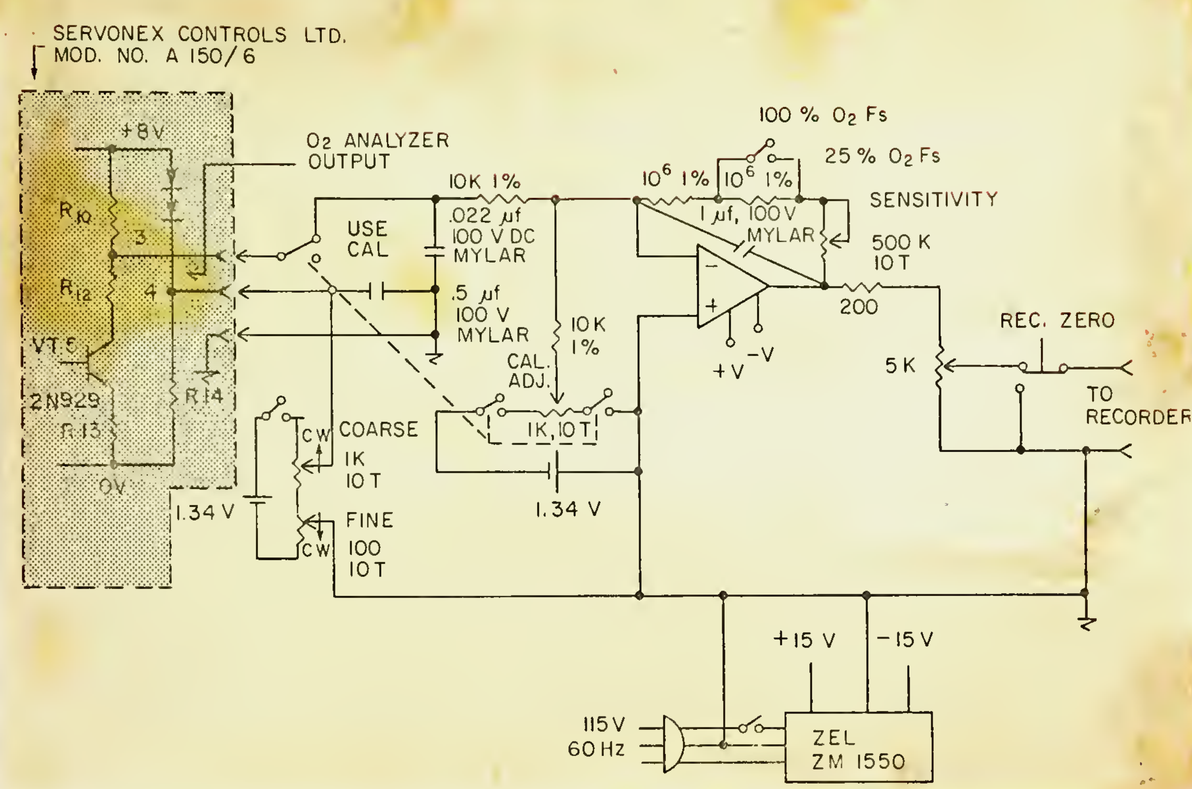

Figure 4. Recorder oxygen analyzer interface.

recorder be 2%, calibrating gas from a tank with an oxygen concentration of about 19% was introduced and the sensitivity of the recorder was adjusted accordingly. The hood was placed over the subject's head and flow rate through the blower was adjusted to approximately 10 to 15 times the expected minute volume of the subject. Although it is not practical nor desirable to have the hood fit tightly over the subject's head, it was found best to have the hood flush with the table as there was always adequate space for air to be drawn in between the subject and the hood. When the recorded oxygen concentration was stable, gas was slowly drawn into a silicone coated syringe through a three-way stopcock and analyzed for carbon dioxide concentration by the micro-Scholander technique.[15]

For correction of $\dot{V}_S$ to STPD conditions, temperature was measured as the gas passed through the flowmeter; barometric pressure was assumed to be the same as ambient pressure; since the room air was only diluted by 5 to 10% with saturated expired air, humidity was assumed to be approximately that of room air. The oxygen analyzer compensates for changes in temperature of $\pm 5^{\circ}C$ of dry gas. Since variation throughout the period of a measurement was rarely more than $1^{\circ}C$, and the gas was dried prior to sampling, no further correction for $F_{S_{O_2}}$ to STPD conditions was necessary.

Assessment of the Method

The stability and accuracy of the pump and flowmeter were evalu-

ated by pumping air out of a Tissot spirometer for two minutes at 10 different settings of the flowmeter.

The accuracy of measuring a known oxygen uptake was assessed by burning ethyl alcohol. For these tests we utilized a modification of Newburgh's apparatus[16] (see figure 5). For each of six trials, 1 ml of ethanol was burned while air was drawn through the hood at various flow rates. Each molecule of ethyl alcohol combusts completely while consuming three molecules of oxygen. Thus, under standard conditions, 1 ml of ethanol used 1.1513×10^3 ml of oxygen.

Ten sequential measurements were made comparing the flow through apparatus to expired gas collections using the Douglas bag. Healthy adults who were familiar with both types of apparatus were selected as subjects. While lying supine, measurements of $\dot{V}_{O_2}$ were made by this system and averaged over three minutes. Immediately following this, expired air was collected in a Douglas bag for a three-minute period. The gas in the bag was measured in a Tissot spirometer and analyzed for oxygen concentration by the micro-Scholander technique. Finally, in one subject several determinations were made of $\dot{V}_{O_2}$ over three-minute periods, but at different flow rates between five and 10 times the minute volume of the subject.

Patient Studies

Oxygen consumption was then measured in 15 infants and children during diagnostic cardiac catheterization. The children were aged from

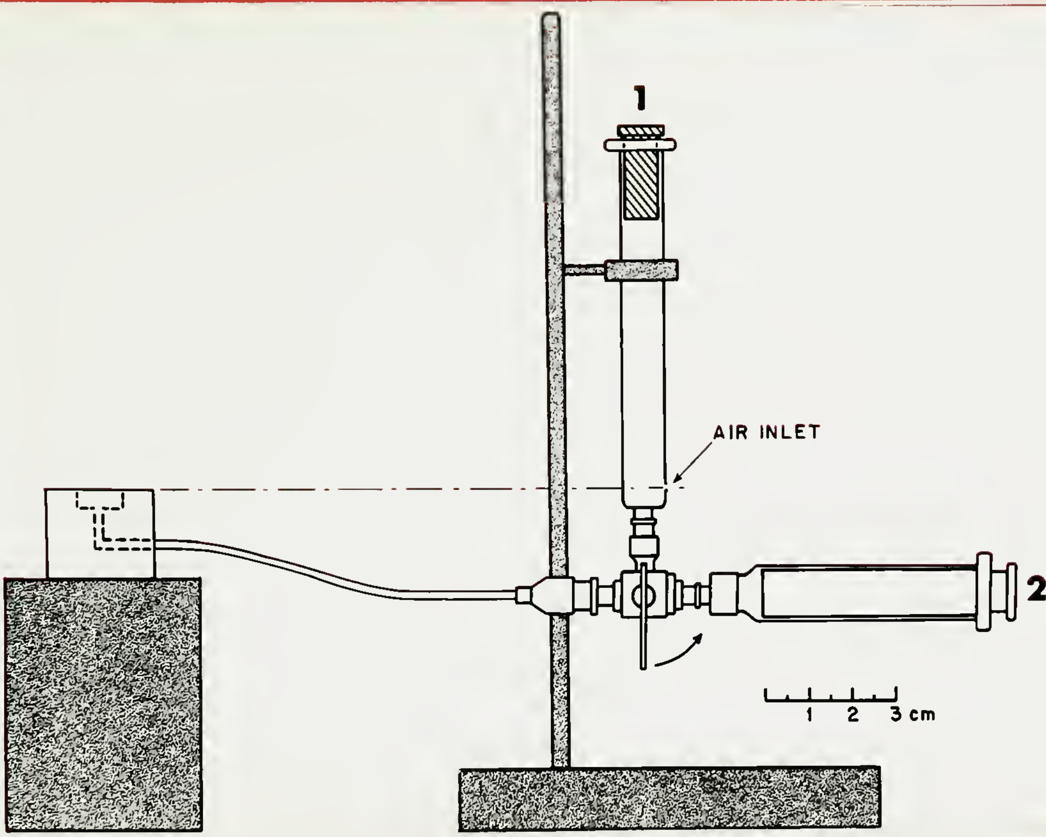

Figure 5. Apparatus for burning ethyl alcohol. While the air inlet is covered, Syringe 1 is filled via the 3-way stopcock from Syringe 2, using 100% ethanol. The stopcock is turned and the dead space in the tubing (#6 teflon catheter) and the brass burning block is filled when the inlet is uncovered. The alcohol in the burner will seek the level of the inlet. Syringe 1 is then refilled and the stopcock is again turned back towards the burner. The alcohol is ignited and the rate of combustion regulated by adjusting the height of Syringe 1, i.e. the level of the air inlet relative to the burner. The burning block is placed under the hood, and time is recorded as a volume of ethanol is burned. As alcohol is burned, the level in the syringe drops and bubbles entering the inlet fill the partial vacuum created between the stopper and the alcohol. The air inlet is small enough that bubbles do not interfere with volume recordings.

two days to eight months. Some had been premedicated with intramuscular meperidine (Demerol[R]) and hydroxyzine pamoate (Vistaril[R]), each 1 mg/kg. Reported measurements are mean values for a five-minute period during which time blood was taken for measurements of oxygen contents.* All children were resting and quiet during the period these measurements were made.

RESULTS

Assessment of the Method

During evaluation of the pump and flowmeter at various flow rates, all spirometric tracings on the Tissot spirometer were straight lines. The pump was, therefore, stable from moment to moment for any given setting. There was, however, variability of 180 ml/min for repeated settings of the flowmeter at the same apparent rate. This represents the discrepancy between flow rate as read on the flowmeter and actual flow rate. At the lowest rates used, the error was 1.6%.

Figure 6 shows the comparison of measured $\dot{V}_{O_2}$ with theoretical $\dot{V}_{O_2}$ determined by burning ethyl alcohol. The slope of the regression line was 0.92 which was not significantly different from the line of identity; the intercept was not significantly different from the origin. The correlation coefficient was 0.99 and the standard deviation of the values was 3.32 ml/min or 4.2% of the mean.

*Lex O_2 Con, Total O_2 Content Analyzer, Lexington Instruments Corp. Waltham, Mass.

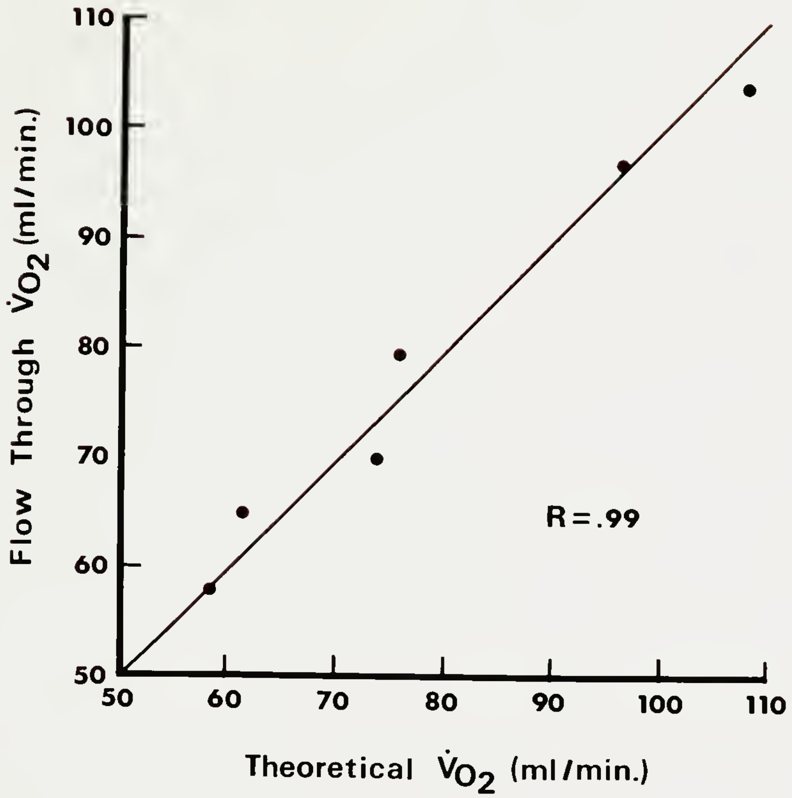

Figure 6. Measurement of $\dot{V}_{O_2}$ by flow through technique compared to theoretical $\dot{V}_{O_2}$ of combusted ethyl alcohol.

Comparison of flows measured on 10 occasions by the flow through method ($\hat{Y}$) and then by the expired gas collection with a Douglas bag (X) gave the equation $\hat{Y} = 0.81X + 45.85$ (see figure 7). The slope was not significantly different from 1.0 and the intercept was not significantly different from the origin ($0.10 > P > 0.05$).

When sequential measurements of $\dot{V}_{O_2}$ were made at different flow rates, the regression line relating flow rate to measured $\dot{V}_{O_2}$ had a slope that did not differ significantly from zero. This indicated that there was no significant change in measured $\dot{V}_{O_2}$ with change in flow rates between five and 10 times the minute volume.

Patient Studies

Oxygen consumption for 15 children measured at the time of cardiac catheterization was 146.4 ± 18.7 ml/min/M^2 or 8.7 ± 1.1 ml/min/kg. Respiratory exchange ratios ranged from .77 to .83. In those children for which no respiratory exchange ratio was reported, the value was assumed to be .9 for purposes of correcting determined $\dot{V}_{O_2}$. These results are summarized in table 1.

DISCUSSION

Historically, two types of methods have been developed to measure $\dot{V}_{O_2}$. 1. With a closed system, a subject is placed in an airtight chamber and, as he breathes, measurements are made of the rate of change of oxygen volume in the chamber, or of the amount of oxygen that must be pumped into the chamber to keep its volume or pressure constant.[1, 17] (Ex-

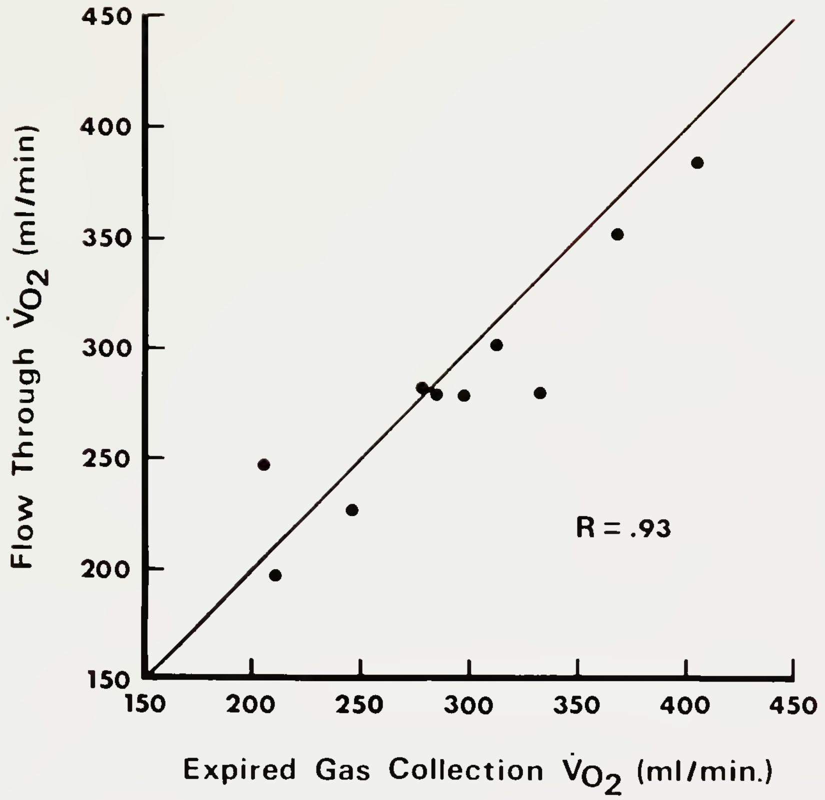

Figure 7. Measurement of $\dot{V}_{O_2}$ by flow through technique compared to $\dot{V}_{O_2}$ determined from expired gas collection using a Douglas bag.

Table 1

Pt.	Age	Diagnosis	Ht.	Wt.	$\dot{V}_{O_2}$	$\dot{V}_{O_2}/M^2$	$\dot{V}_{O_2}$/kg	R
1	$7\frac{1}{2}$ m.	VSD	58	3.8	39.1≠	162.9	10.3	
2	6 m.	Corr. TGV VSD	68	6.3	56.8	167.1	9.0	
3	7 wk.	EFE	59	4.3	51.8	199.2	12.0	
4	2 wk.	AS	52	3.6	29.4	133.6	8.2	
5	5 m.	VSD	61	4.3	47.5≠	183.7	11.0	
6	8 m.	PDA	68	6.9	49.2≠	140.6	7.1	
7	4 m.	Lobar Emphysema	59	5.6	42.0∤	144.8	7.5	
8	3 d.	TGV ASD	55*	3.4	26.0	118.2	7.6	
9	7 d.	VSD	55	3.8	31.5	137.0	8.3	
10	2 m.	Single Ventricle	57	3.9	35.9	150.0	9.2	
11	6 m.	TAPVR	61	6.0	53.4	178.0	8.9	
12	20 d.	TGV VSD	55	3.1	25.1	119.5	8.1	
13	2 d.	TGV	56	4.9	33.1	127.3	6.8	
14	3 m.	VSD	59	3.9	23.4≠	94.6	6.0	.77
15	2 m.	Mass Right Pleural Cavity	58	3.0	30.8	139.8	10.3	.83
						m=146.4 $\pm$ 27.7	m= 8.7 $\pm$ 1.7	

* Estimated

Premedicated with: ≠ Demerol^R, Vistaril^R 1 mg/kg each

∤ Demerol^R 1 mg/kg

pired carbon dioxide and water vapor are absorbed so that the changes in the system are due only to consumed oxygen.) Although of value for metabolic studies, this system leaves the subject relatively inaccessible while oxygen consumption is being measured. As a result it is difficult to measure $\dot{V}_{O_2}$ simultaneously with arterial and venous oxygen contents, so that this method is not practical for blood flow calculations during cardiac catheterization.

2. With an open system, the subject is part of an open circuit in which he continuously breathes fresh room air and his expired gas is collected for measurement of volume and concentrations of oxygen and/or carbon dioxide.[2, 14] The simplest design based on this principle utilizes a two way valve, permitting the subject to breathe in room air through a nose or mouth piece while his expired volume is collected in a bag or spirometer.[18] The difficulty is that this requires cooperation from the subject and necessitates the use of a nose or mouthpiece which may be uncomfortable; it is thus of limited value in infants and small children, except for the group of young infants who are obligate nose breathers. Therefore, a more complex type of open system, the flow through apparatus, which has long been of value in metabolic studies,[14, 19-21] has come into use during cardiac catheterization. With this system, two dependent variables must be measured: flow rate of gas through the system and oxygen or carbon dioxide concentration of the expired gas-room air mixture. As the flow rate is increased, the difference between the

oxygen (or carbon dioxide) concentrations of room air and mixed expired gas decreases. Since flow rates are usually kept at least five to 10 times the subject's minute volume to prevent loss of expired air from the system, the sampled oxygen and carbon dioxide concentrations will be very close to those of room air; the instruments used must be capable of measuring these small differences accurately.

While it is possible to determine oxygen consumption without measuring carbon dioxide production, there are two reasons for making the latter measurement. Although most infants probably have an R value of .85 to .90,[1] it is possible for those who are very ill to have unusually high or low respiratory exchange ratios, particularly if they are changing from one type of metabolic fuel to another. It is, therefore, possible to be in error by as much as 10% in measuring $\dot{V}_{O_2}$ if R is assumed to be 1.0. As R is an independent variable, this error is in no way reduced by making flow rates high relative to minute volume, as has been previously suggested.[11, 12] Calculation of R also leads to better assessment of metabolism which would be of interest and importance in very sick children.

Although it is feasible with the present system to measure continuously the carbon dioxide concentration of mixed expired gas, there is no simple, inexpensive apparatus available for this purpose. We, therefore, took gas samples intermittently and analyzed them by the conventional micro-Scholander technique to compute $\dot{V}_{CO_2}$. With early flow

through systems, a similar procedure was followed to obtain $\dot{V}_{O_2}$; since equipment was not available for continuous monitoring of oxygen concentration, the room air-expired gas mixture was colledcted and analyzed at the end of the testing period.

The advantages of measuring continuous oxygen concentrations, however, are that:

1. it is possible to determine when there is a steady state, and
2. it is possible to measure $\dot{V}_{O_2}$ in the unsteady state if these values are desired.

Devices developed to monitor gaseous oxygen have made use of one of oxygen's specific physical or chemical properties in order to distinguish it from other gases in a mixture.[22] Atomic weight, being unique, theoretically is the most suitable for this purpose. The mass spectrometers, however, are expensive and not yet available for physiologic measurements.[23]

The diaferometer,[24] one of the first types of continuous analyzers developed, has been used in Europe and to a limited extent in this country.[1, 3, 9, 25] It utilizes thermal conductivity as a parameter for measurement. This property, however, is not specific to oxygen, and carbon dioxide concentration and temperature must be carefully controlled, rendering the instrument technically difficult to operate.

In 1845, Faraday recognized that oxygen, when placed in a magnetic field, would develop a magnetic moment in the direction of that field and in proportion to the field strength. This tendency to move into

through crystals, [illegible] composition was not [illegible] ration, [illegible] the end of the earlier period.

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a region of maximum magnetic flux is known as paramagnetism. Of the common gases oxygen is unique in its strong paramagnetic properties. Most other gases, being slightly diamagnetic, tend to be repelled by a magnetic field. Since the magnetic forces acting on oxygen differ from those acting on other common gases in both direction and order of magnitude, it is an ideal parameter for measurement and permits oxygen to be easily detected when present in small quantities in a gas mixture.

Pauling, in 1940, developed a paramagnetic cell for continuous measurement of oxygen tension which serves as the basis for many modern oxygen analyzers. The cell[25] is designed such that a small hollow glass dumbbell is suspended by a taut fiber between two poles of a magnet. The dumbbell is filled with a very weakly diamagnetic gas; if the surrounding gas is also diamagnetic, it is oriented toward an area of high flux due to the tension of the fiber. When a paramagnetic gas (oxygen) enters the field, the gas in the dumbbell becomes strongly diamagnetic relative to its surroundings. The diamagnetic gas is then forced out of the region of maximum flux thereby rotating the dumbbell and inducing torque in the fiber. The displacing force is proportional to the partial pressure of the paramagnetic gas introduced, and may be quantitated in one of two ways:

1. A mirror may be fixed to the dumbbell from which a beam of light is reflected. The shift of the beam along a calibrated scale is a measure of the degree of displacement.
2. A coil of wire may be placed around the dumbbell and a current induced from electrodes tending to rotate the

dumbbell back to its initial, or null, position and counter-balancing the torque induced by the paramagnetic gas. The magnitude of the current needed is thereby a function of the force of displacement. This is the principle of the null type indicator and has proven to enhance the accuracy of the instrument.[22]

The early paramagnetic oxygen analyzers[27] used a quartz fiber to suspend the dumbbell. However, with the quartz suspension the force on the dumbbell diminishes per unit increase in oxygen tension, therefore, decreasing the sensitivity. This type of instrument has been used successfully during cardiac catheterization for continuous measurement of oxygen concentration,[10, 11] yet because of this technical difficulty it may be unstable and require frequent recalibration.

Recently, a new paramagnetic analyzer was developed utilizing a null type indicator and a platinum iridium suspension which has proven to be more robust than quartz.[28] Preliminary tests have shown this instrument to be both accurate and stable,[12, 28, 29] however, it has not yet been tested for continuous <u>in vivo</u> measurement of oxygen consumption. The method described uses this new paramagnetic oxygen analyzer; the accuracy of the system was tested by measuring known uptake of oxygen, and comparisons were made of $\dot{V}_{O_2}$ measured with this method and the conventional expired gas collection using a Douglas bag.

That the system can measure known oxygen consumption accurately

is demonstrated by the alcohol experiments and confirms the results obtained with an introduced nitrogen method,[12] i.e., displacing flow through room air with a known amount of nitrogen and comparing theoretically displaced oxygen with measured $\dot{V}_{O_2}$. In our apparatus for burning alcohol, there was virtually no likelihood of evaporation of the alcohol: Had any substantial amount of alcohol been lost then the amount of oxygen consumed would have been consistently less than the estimate.

The standard deviation of 3.32 ml/min, or a coefficient of variation of 4.2%, could be due to variability of measurement of flow rate or of the measurement of oxygen concentration. Nunn has shown that the oxygen analyzer is linear, precise, and stable, suggesting that measurement of the flow rate is the main cause of this small variability.[29]

Another potential source of error resides in the calibrating gas. If it is incorrectly analyzed, then all measurements made when it is used will have a consistent bias; however, this will not contribute to variability. Comparison of the means for measured and theoretical $\dot{V}_{O_2}$ demonstrated no such bias (79.42 ml/min as opposed to 79.20 ml/min).

The comparison of $\dot{V}_{O_2}$ determined by the flow through method and the expired gas collection showed more variability. Not only might there have been variability of actual $\dot{V}_{O_2}$ in the two time periods, but the use of a nose clip and mouthpiece produces minor discomfort and might be expected to increase oxygen consumption. Nevertheless, the relatively good comparisons of $\dot{V}_{O_2}$ measured by the two methods indicates that in

practice the flow through system is likely to be as accurate as the *in vitro* tests suggest.

The fact that at different flow rates the $\dot{V}_{O_2}$ values were unaltered shows that there was no loss of expired air from the system at the lowest flow rates. Flow rates lower than those that we used certainly would increase the difference between the oxygen concentrations of inspired and mixed expired gas, and so reduce any error introduced by the oxygen analyzer. However, at low flow rates expired air might leak out of the hood. Since the oxygen analyzer has been shown to be sensitive to small changes in oxygen concentrations, it is advantageous to use high flow rates in order to minimize the effect of breath to breath variation in $\dot{V}_{O_2}$, thereby providing a more stable record.

The values for $\dot{V}_{O_2}$ obtained in our patients (146.4 ml/min/M^2 or 8.7 ml/min/kg)correlate well with those reported by others; 198 $\pm$ 33 $\dot{V}_{O_2}/M^2$ in 18 infants at catheterization;[6] 156 $\dot{V}_{O_2}/M^2$ in 14 infants up to one year of age at catheterization;[11] 10.8 $\pm$ 2.4 $\dot{V}_{O_2}$/kg in 23 sedated infants;[9] 6.5 - 10.0 $\dot{V}_{O_2}$/kg in 11 infants.[8] Since there has been no accepted parameter for which to standardize oxygen consumption, we chose to report values in terms of both body surface area and weight. The standard deviation of $\dot{V}_{O_2}$ determined by the present method was 27.7 ml/min/M^2 or 17% of the mean. Since this is not error of the method, it reflects large biological variability amongst a group of infants and demonstrates why it is important, whenever possible, to measure

actual $\dot{V}_{O_2}$ rather than rely on standardized tables or regression equations.

SUMMARY

A method has been described for continuous measurement of oxygen consumption and determination of carbon dioxide production and respiratory exchange ratio. The apparatus is portable, simple to operate, and inexpensive. Thus, the method appears ideally suited for measurement of respiratory gas exchange in infants and children in both steady and unsteady states. The accuracy of the method was confirmed by comparison to theoretical oxygen consumption from burning ethyl alcohol and to measured $\dot{V}_{O_2}$ from expired gas collection. Oxygen consumption in 15 infants between two days and eight months measured at the time of cardiac catheterization was 146.4 ± 27.7 ml/min/M^2 or 8.7 ± 1.7 ml/min/kg.

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APPENDIX

Symbols:

$\dot{V}$ =volume of gas flow per unit time (ml/min)

$\dot{V}_S$ =flow through system

$\dot{V}_L$ =flow of room air drawn into hood

$V_{I,\,E}$=volume of inspired and expired gas

$\dot{V}_{O_2}$ =oxygen consumption

$\dot{V}_{CO_2}$ =carbon dioxide production

R =respiratory exchange ratio ($\dot{V}_{CO_2}/\dot{V}_{O_2}$)

F =fractional concentration of a gas in a mixture

F_S =concentration in sampled mixed expired gas

$F_{I,\,E}$=concentration in inspired and expired gas

Since $\dot{V}_S = \dot{V}_L - \dot{V}_I + \dot{V}_E$,

then $\dot{V}_L - \dot{V}_S = \dot{V}_I - \dot{V}_E = \dot{V}_{O_2} - \dot{V}_{CO_2}$.

Since $R = \dot{V}_{CO_2}/\dot{V}_{O_2}$,

therefore $\dot{V}_L - \dot{V}_S = \dot{V}_{O_2} - R\dot{V}_{O_2} = \dfrac{\dot{V}_{CO_2}}{R} - \dot{V}_{CO_2}$. (eq. 1)

Derivation of V_{O_2}:

$$\dot{V}_{O_2} = \dot{V}_L F_{I_{O_2}} - \dot{V}_S F_{S_{O_2}} ,$$

therefore $\dot{V}_{O_2} = F_{I_{O_2}} (\dot{V}_S + \dot{V}_{O_2} - R\dot{V}_{O_2}) - \dot{V}_S F_{S_{O_2}}$ (from eq. 1)

and $\dot{V}_{O_2} = \dot{V}_S (F_{I_{O_2}} - F_{S_{O_2}}) + \dot{V}_{O_2} F_{I_{O_2}} (1-R)$.

Therefore $\dot{V}_{O_2} (1 - F_{I_{O_2}} (1-R)) = \dot{V}_S (F_{I_{O_2}} - F_{S_{O_2}})$,

and $\dot{V}_{O_2} = \dot{V}_S (F_{I_{O_2}} - F_{S_{O_2}}) / (1 - F_{I_{O_2}} (1-R))$.

Since $F_{I_{O_2}} = 0.2093$, the concentration of oxygen in room air,

then $\dot{V}_{O_2} = \dot{V}_S (0.2093 - F_{S_{O_2}}) / (0.7907 + 0.2093R).^*$ (eq. 2)

Note that if $R = 1$, then the denominator of this expression disappears, leaving the equation usually used to calculate $\dot{V}_{O_2}$ by the flow through method. If R were 0.7 (using only fat for metabolic fuel), then $\dot{V}_{O_2}$ would be underestimated by 7% from the formula that ignores the value of R. This is the greatest error that can be made in a steady metabolic state. However, lower R values may occur so that on sick children it would be best to measure R. The value of $(0.2093 - F_{S_{O_2}}) / (0.7907 + 0.2093R)$ may be obtained from the nomogram in figure 8 or from inset in back cover.

Derivation of V_{CO_2}:

$$\dot{V}_{CO_2} = \dot{V}_S F_{S_{CO_2}} \; \dot{V}_L F_{I_{CO_2}},$$

therefore $$\dot{V}_{CO_2} = \dot{V}_S F_{S_{CO_2}} - F_{I_{CO_2}}(\dot{V}_S + \frac{\dot{V}_{CO_2}}{R} - \dot{V}_{CO_2}) \quad \text{(from eq. 1)}$$

and $$\dot{V}_{CO_2} = \dot{V}_S(F_{S_{CO_2}} - F_{I_{CO_2}}) - F_{I_{CO_2}} \dot{V}_{CO_2}(\frac{1}{R} - 1).$$

Rearranging $$\dot{V}_{CO_2}(1 + F_{I_{CO_2}}(\frac{1}{R} - 1)) = \dot{V}_S(F_{S_{CO_2}} - F_{I_{CO_2}}),$$

therefore $$\dot{V}_{CO_2} = \dot{V}_S(F_{S_{CO_2}} - F_{I_{CO_2}}) \;/\; (1 + F_{I_{CO_2}}(\frac{1}{R} - 1)).$$

Since $F_{I_{CO_2}} = 0.0003$, the concentration of CO_2 in room air,

then $$\dot{V}_{CO_2} = \dot{V}_S(F_{S_{CO_2}} - 0.0003) \;/\; (0.9997 + \frac{0.0003}{R}).$$

If R varies from 0.67 to 1.33, the denominator varies from 0.999925 to 1.00015. Thus, if we assume that the denominator is 1, the error is less than 0.00015,

therefore $$\dot{V}_{CO_2} = \dot{V}_S(F_{S_{CO_2}} - 0.0003).^{*} \quad \text{(eq. 3)}$$

*Note that values for $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ must be corrected to STPD conditions. To correct volumes for STPD:

$$\dot{V}(STPD) = \dot{V}(observed) \times \frac{273}{(T+273)} \times \frac{P_B - P_{H_2O}}{760}$$

where T = ambient temperature in ^oC, P_{H_2O} = water vapor pressure at T, P_B - ambient pressure in mm Hg.

<u>Derivation of R:</u>

From (eq. 2) and (eq. 3),

$$\frac{1}{R} = \frac{\dot{V}_{O_2}}{\dot{V}_{CO_2}} = V_S(0.2093-F_{S_{O_2}}) / V_S(F_{S_{CO_2}}-0.0003)(0.7907+0.2093R)$$

therefore $(0.7907+0.2093R)/R=(0.2093-F_{S_{O_2}})/(F_{S_{CO_2}}-0.0003)$,

and $$R = \frac{0.7907}{(0.2093-F_{S_{O_2}})/(F_{S_{CO_2}}-0.0003) \quad 0.2093} .$$

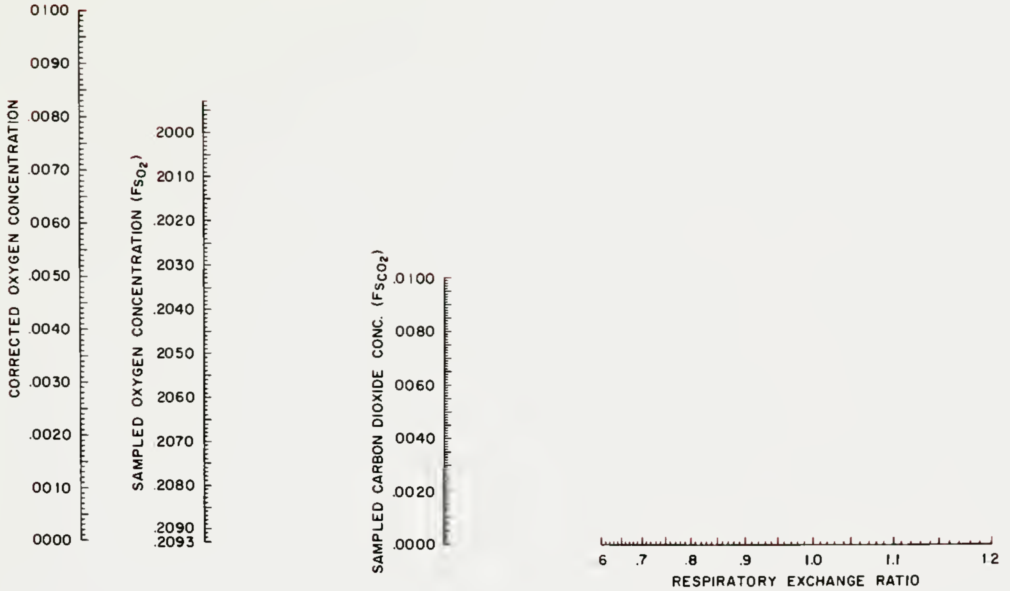

Figure 8. Nomogram for correcting sampled gas for variations in respiratory exchange ratio. Locate points on "sampled oxygen concentration" and "sampled carbon dioxide concentration" scales corresponding respectively to the oxygen and carbon dioxide concentrations of the mixed expired gas ($F_{S_{O_2}}$ and $F_{S_{O_2}}$). Place a straightedge along these points. The respiratory exchange ratio may be read directly from the scale. The corrected oxygen concentration obtained is equal to:

$$(0.2093 - F_{S_{O_2}}) / (0.7907 + 0.2093\ R).$$

This value, when multiplied by $\dot{V}_S$ (STPD), gives the true oxygen consumption. (See back inset for full scale nomogram.)

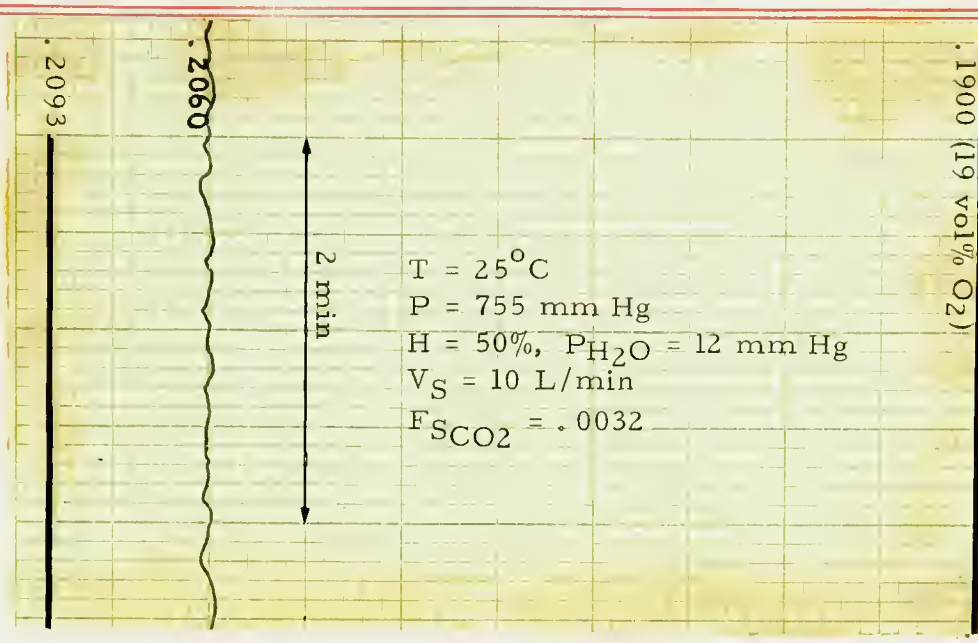

Figure 9. Sample calculation of $\dot{V}_{O_2}$, $\dot{V}_{CO_2}$ and R.

From tracing $F_{S_{O2}}$=.2060,

by gas analysis $F_{S_{CO_2}}$=.0032,

therefore Corrected O_2 concentration=.0034

and R=.85 (from nomogram).

$$\dot{V}_S(STPD) = \frac{273}{298} \times \frac{755-12}{760} \times 10 \text{ l/min} = 8.95\text{x}10^3 \text{ ml/min.}$$

From eq. 2 $\dot{V}_{O_2}(STPD)=8.95\text{x}10^3 \times 3.4\text{x}10^{-3}=30.4$ ml/min.

From eq. 3 $\dot{V}_{CO_2}(STPD)=8.95\text{x}10^3 (.0032-.0003)=26.0$ ml/min.

Nomogram for correcting sampled gas for variations in respiratory exchange ratio

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